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Acoustics of a Mixed Porosity Felt Airfoil

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PREFACE

This document was prepared under NUWC Division Newport NWA 100001120189/0010, principal investigator Aren M. Hellum (Code 8514). The sponsoring activity is the In-house Laboratory Independent Research project "Acoustics and Performance of Lifting Surfaces with Mixed Porosity."

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14. ABSTRACT

Lifting surfaces produce noise in operation, and porous materials have been shown to reduce this noise. Acoustic measurements were made on three arrangements of poroelastic material: full-chord porosity, full-chord impermeability, and mixed porosity. A scaling scheme is presented that collapses the spectra acquired at different Reynolds numbers. The results are compared to applicable published data. The noise reduction produced by the mixed porosity arrangement is found to be similar to the fully-porous arrangement at low Reynolds numbers. The noise reduction produced by the mixed and fully-porous foils does not match over the entire frequency range at higher Reynolds numbers.

15. SUBJECT TERMS

wings, hydrofoils, propulsor blade, stall, shed vortices, trailing edge scattering, owl, mixed porosity, poroelastic boundary layer

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ABBREVIATIONS AND ACRONYMS

3D	Three Dimensional
NUWC	Naval Undersea Warfare Center
pwelch	Power Spectral Density, Welch's method

1. INTRODUCTION

Lifting surfaces such as wings, hydrofoils, and propulsor blades produce noise in operation. This noise has several potential sources, including stall, shed vortices, and trailing edge scattering [1] [2]. Although the porous wings of owls have been shown [3] [4] to reduce the noise produced in flight, it is not clear at present what mechanisms operate to produce this noise reduction. It is worth investigating the form of solution favored by owls, the mixed-porosity wing, in which some fraction of the lifting area is porous and the rest is impermeable.

The potential acoustic benefits of porous foils can be estimated from existing literature. Geyer *et al.* [5] measured a sound reduction of 5 to 15 dB for airfoils made entirely of porous material. A 1973 patent awarded to Hayden and Chanaud [6] describes measurements using a porous foil in air, finding an 8- to 18-dB improvement over a reference solid foil. That patent also describes a number of mixed porosity arrangements, but does not specify a preferred arrangement. The patent literature on this topic is extensive [7] [8] [9], but typically lacks quantitative claims. The literature also contains other sources pertaining to porous lifting surfaces that are concerned primarily with cooling high-temperature turbine blades [10] or mitigating shock waves [11] [12]. Theoretical work on a poroelastic boundary layer by Jaworski and Peake [13] discovered less effect than the experimental works, finding a maximum improvement of 6 dB for a rigid, porous edge and up to 12 dB for a poroelastic edge.

Porous materials can be parameterized in several ways. The inviscid model developed in [13] incorporates the bending wavenumber and density ratio between the fluid and foil. This model indicated that the flexible trailing edge of an owl's wing was responsible for most of that animal's ability to reduce trailing-edge noise. Hayden and Chanaud [6] use the specific acoustic impedance of the porous material relative to the surrounding medium. The pressure drop of air through a unit thickness of the material (resistivity) has also been used to describe the porous material [5]. Resistivity is fluid- and material-dependent. Various low-level porous material identifiers—such as nominal pore size and fiber diameter—have also been employed [14] [15]. These parameterizations are not readily comparable, so the tests presented in this report use a strong-performing material from previous studies to examine mixed-porosity arrangements.

The lack of consensus regarding the parameterization of porous lifting surfaces reflects a similar confusion about the mechanisms at work, but it is generally held that porous materials weaken the noise scattering mechanism at the trailing edge. As the boundary layer convects past the trailing edge, the pressure field goes from being supported by the foil surface to being unsupported in the wake, scattering half of its energy in the process [8]. The porous area fraction and porous material parameters that can beneficially interact with the noise scattering mechanism are not clear at present.

In this report, measurements taken for three porous area fractions are presented, with a scaling scheme that collapses the frequency and amplitude of data acquired at different Reynolds numbers. The noise reduction produced by the fully-porous arrangement is shown to match the most-applicable published data. The noise reduction produced by the mixed porosity arrangement is found to be similar to the fully-porous arrangement at low Reynolds numbers over the frequency range measured. The noise reduction produced by the mixed and fully porous foils does not match over the entire frequency range at higher Reynolds numbers. These trends in noise reduction and possible explanations for the effect are discussed in this report.

2. RESULTS

The present data were acquired in the 48-inch acoustic wind tunnel (figure 1A) at the Naval Undersea Warfare Center (NUWC) in Newport, RI. The test item used was made of a dense felt that was laser cut into an NACA0012 airfoil shape with an 11.5-inch chord. The porous section's 24-inch span was constructed from ¾-inch sections, as shown in figure 1B. The alignment shafts were used to support the foil during the test. The porous section is shown in 100%- and 54%-porous configurations in figures 1C and 1D. The remainder of the 53-inch span is made of 3D-printed ABS plastic (blue in figures 1A, 1C, and 1D); this span ensures that the airfoil tips are not in the flow. Additional details regarding the setup, data acquisition, and processing are provided in section 4.

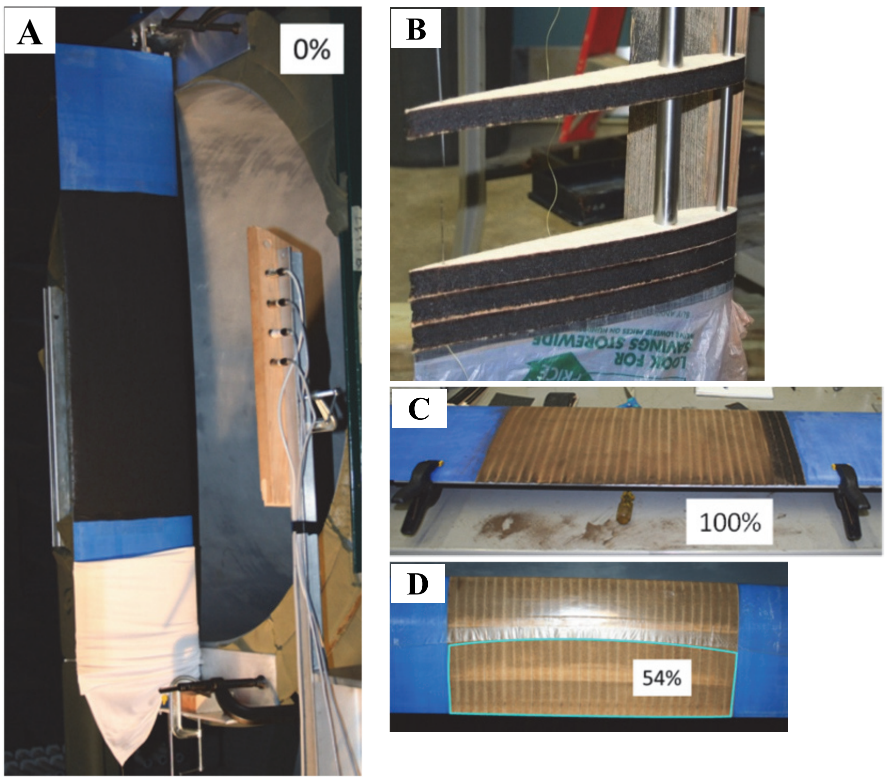

Figure 1. Mixed-Porosity Test Item in Place and Under Construction

Note: Details for images in figure 1: (A) NUWC's 48-inch acoustic wind tunnel. The test item is in the 0% porous area configuration; the full-chord fairing is the central black section. The four-element microphone array is at right. The spandex cover (white) that was stretched over the length of the test item during all tests has been removed and is at the bottom of the foil. (B) Felt section during construction; alignment shafts are at the right of the image. Trailing edge thread (section 4.2) is shown at the left of the image. (C) Test item in the 100%-porous area fraction configuration during construction. The darker color at right is the

unremoved char layer (section 4.2). (D) Test item in 54%-porous area fraction configuration. The porous trailing edge is outlined.

The unscaled spectrum associated with each porous area fraction is shown in figure 2 over a range of Reynolds numbers. These data were taken over the range U_∞ =18.4-30.5 m/s. The chord Reynolds number $U_\infty L_c/\nu$ is shown in each plot to indicate the tunnel speed. The elevated noise produced by the 100%-porous foil at high frequencies has been noted in previous studies; this phenomenon is investigated further in section 3.

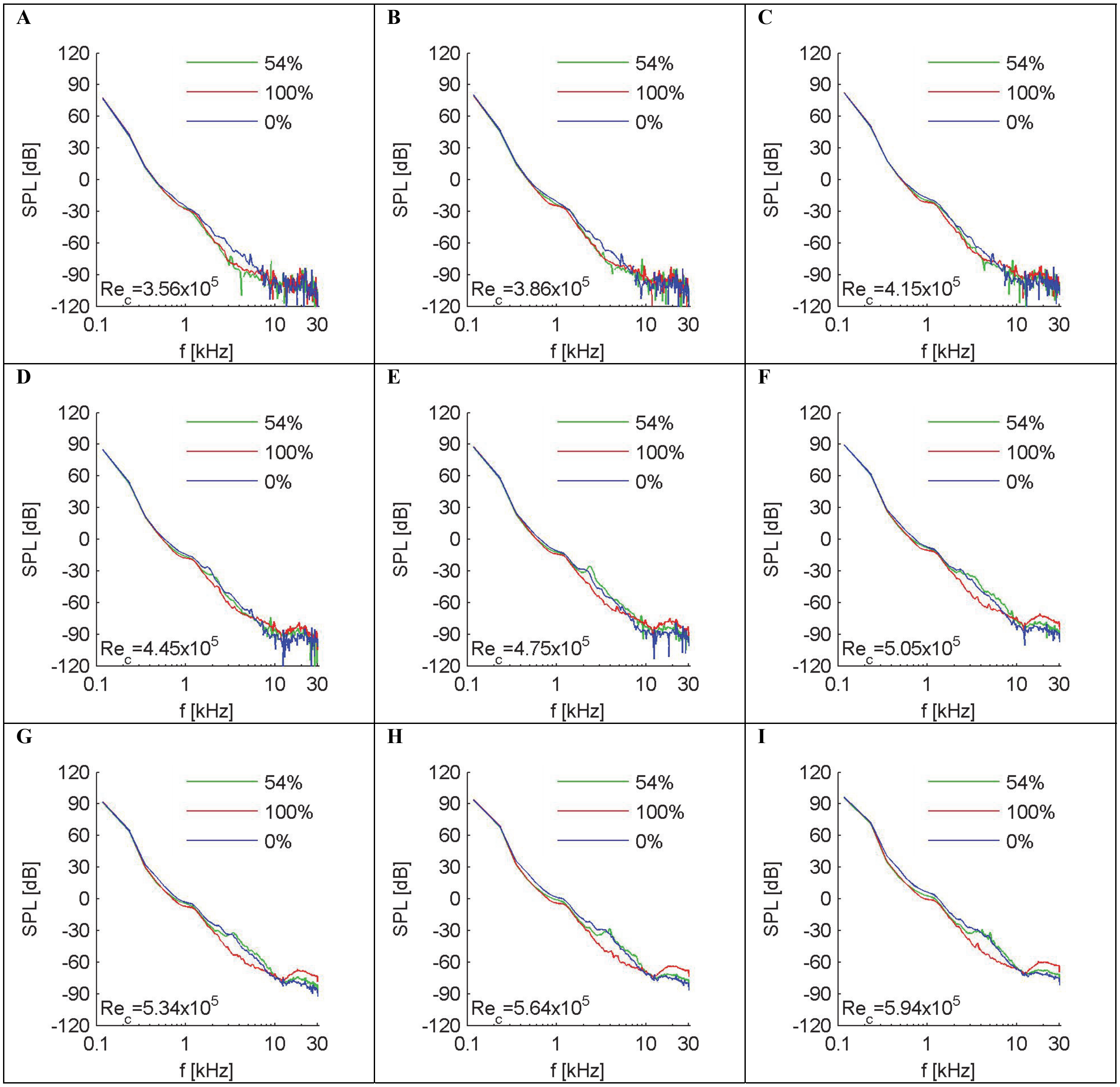

Figure 2. Unscaled Spectra

Note: In figure 2, the Reynolds number increases from A to I.
The legend indicates the porous area fraction.

Figure 2 also indicates that—as expected—the frequency and amplitude of the sound produced by the foils are functions of the free-stream velocity. A scaled version of the plots is shown in figure 3, where the relationship [16]

$$SPL_{scaled} = SPL - 10\log_{10} U_\infty^5 \text{ dB}$$

is used to scale the ordinate. The abscissa has been scaled using a Strouhal number based on the maximum thickness of the foil:

$$St_d = \frac{f(0.12c)}{U_\infty}$$

where the constant 0.12 is used because of the foil shape being tested (NACA0012). This scaling scheme produces spectra that are of reasonably constant amplitude for all speeds at low Strouhal numbers. The noise reduction of each porous arrangement can be obtained by subtracting the spectrum produced by the 0%-porous foil from that of each porous arrangement. The noise reduction is shown in figure 4. It is interesting that at $Re_c = 3.56 * 10^5$, the noise reduction of the 54%-porous foil essentially tracks that of the 100%-porous foil over the entire range of Strouhal numbers. At higher Re_c, the two porous arrangements clearly diverge. This transition is investigated further in section 3.

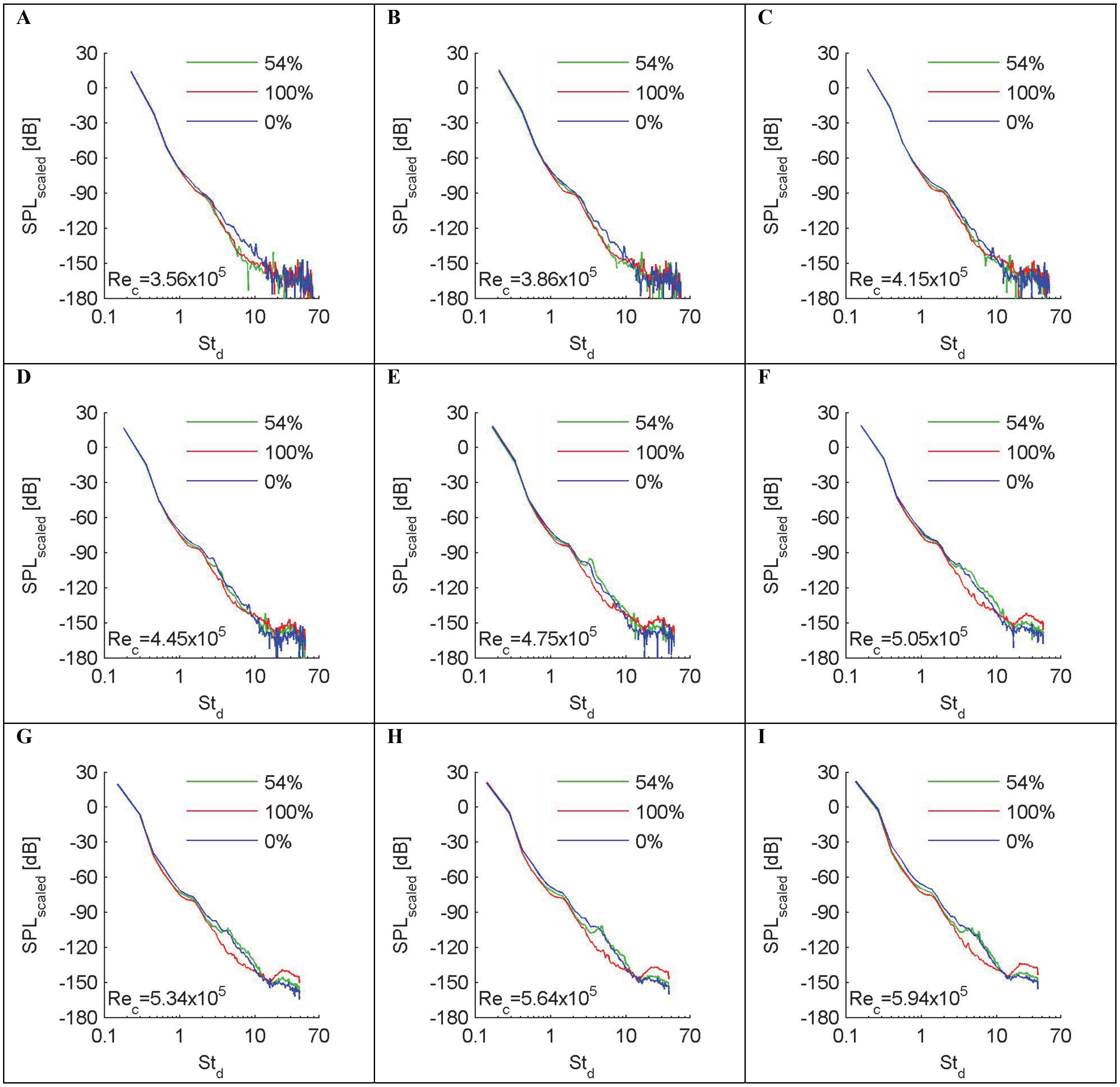

Figure 3. Scaled Spectra

Note: In figure 3, the Reynolds number increases from A to I.
The legend indicates the porous area fraction.

3. DISCUSSION

3.1 COMPARISON WITH PUBLISHED RESULTS

The present data from this report are compared with the previously-published data of Geyer *et al.* [5] and Herr *et al.* [14] in figure 5. Relevant parameters of each study are provided in table 1. The published studies tested multiple porous materials and only the one being compared is listed. The published works used a separate rigid airfoil or insert as an impermeable baseline while the present data covered the felt foil with a thin plastic membrane to approximately preserve the elastic qualities of the foil.

Table 1. Relevant Parameters of Present and Published Experimental Investigations of Porous Airfoils

	Porous Material	Shape	Thickness	Area Fraction	Re_c	Array
Present	Dense felt	NACA0012	35 mm	100%, 54%	5.9×10^5	Line, 4 element
Geyer	Dense felt	SD7003	20 mm	100%	1.0×10^6	Planar, 56 element
Herr	Sintered fiber felt	“DLR-F16 model”	37 mm	10%	1.3×10^6	Planar, 96 element

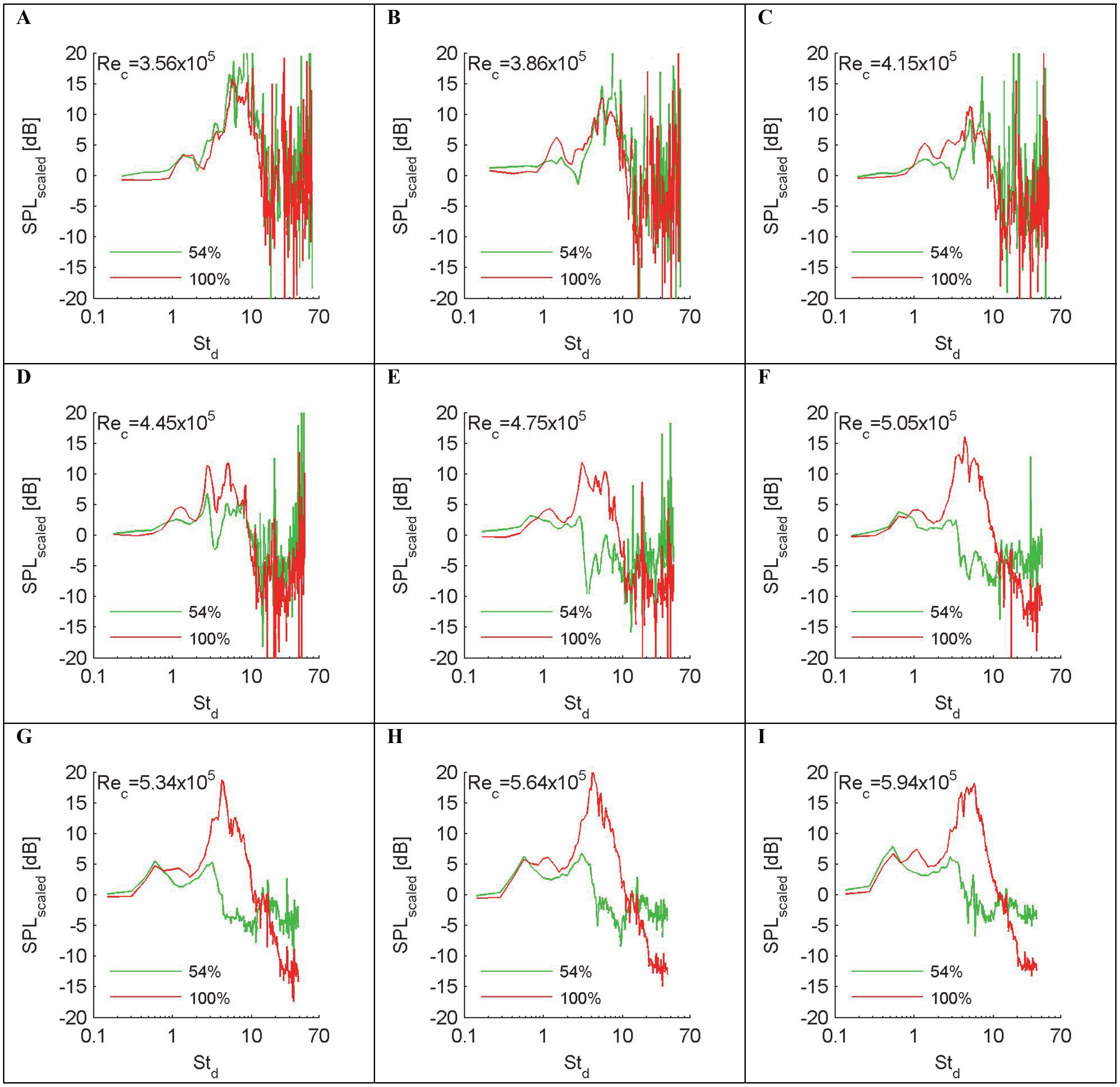

Figure 4. Noise Reduction Produced by each of the Porous Foil Arrangements Relative to the Baseline 0%-Porous Foil

Note: In figure 4, the Reynolds number increases from A to I. The legend indicates the porous area fraction from which the baseline is subtracted.

The similarity between the two 100%-porous curves is striking in light of the differences between the present data in this report and the Geyer *et al* [5]. studies. Because the experiments presented here used a non-rigid impermeable baseline, this similarity indicates that the elasticity of the foil is a secondary factor in noise reduction [13]. The noise reduction measured by Herr [14] at the 10%-porous area fraction is similar to the 54%-porous data presented in this report. The fact that the partially-porous foils show similar levels of noise reduction at two very different porous area fractions is interesting, and additional studies are planned to investigate this further.

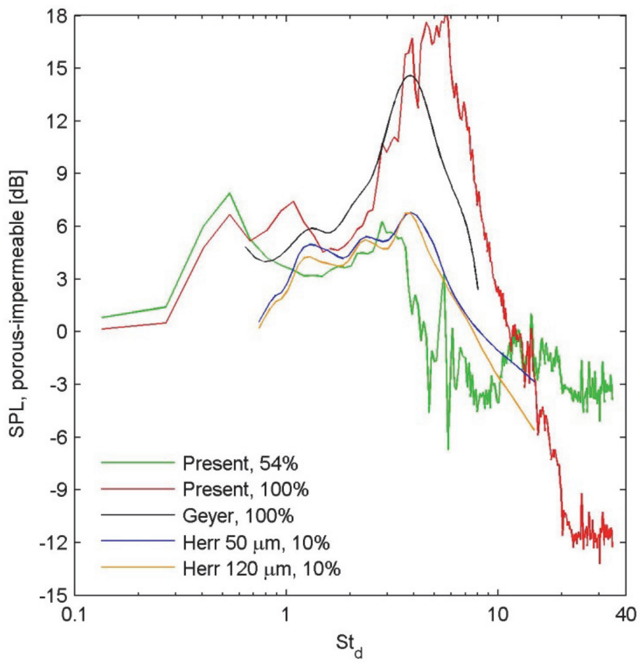

Figure 5. Noise Reduction Data from Present Study, Geyer et al. [5] and Herr et al. [14]

> **Note:** In figure 5, the present data were collected at $Re_c = 5.94 \times 10^5$. The percentage indicates porous area fraction and the number indicates the pore size.

Each study indicates increased trailing-edge noise at high frequencies; data reflecting this do not appear in Geyer's figures, but it is indicated in that work's text. One theory proposed to explain this phenomenon [5] [14] attributes this elevated noise to the difference in surface roughness between the porous and reference surfaces. This explanation is unsatisfactory based on the results produced by this report, wherein a fabric cover was placed over the foil to preserve the surface roughness between porosity conditions.

This situation is reminiscent of the flow treatment used in wind tunnels, whereby velocity gradients are flattened by restriction and vortical motions are broken up by honeycomb [17]. In this way, the energy in large, low-frequency motions is shifted to smaller motions that dissipate more rapidly. A similar mechanism holds in acoustic transmission [18], such that

$$A(\omega, x) = A_0(\omega)\exp(-\kappa\omega^2 x)$$

where A is the measured amplitude at some frequency ω and distance x, A_0 is a frequency-dependent source amplitude, and κ is a medium-dependent constant. This indicates that despite producing similar levels of acoustic energy when integrated over the spectrum, a porous foil would be expected to reduce the acoustic signature because high frequencies are more strongly attenuated with distance.

The mechanism by which this shift in energy occurs is not clear at present, but the wind tunnel analogy may be instructive. Pressure variations near a porous surface induce flows within the medium that percolate out of the porous surface. These percolating flows are subjected to breakup by the porous medium, shifting the energy to higher frequencies.

3.2 NOISE REDUCTION TREND WITH REYNOLDS NUMBER

The noise-reducing qualities of the 100%-porous and 54%-porous foils do not react the same way to increasing Reynolds number. This phenomenon is shown in figure 6; for $Re_c \geq 4.75 * 10^5$, the spectrum of the 54%-porous foil diverges from the 100%-porous foil at $St_d \geq 2.5$. The Reynolds number range at which this occurs indicates the possible role of turbulent transition [19], but this is not deemed likely at this time.

In addition to the care taken to trip the flow (section 3.1), tufting was performed, which indicated that the foil was not experiencing laminar separation [20] over the range of Reynolds numbers being tested. However, the tufting tests were performed in the very early stages of the experiment to determine whether the typical stall behavior of a NACA0012 airfoil was recovered and should not be treated as definitive at this writing. Further tufting and hotwire anemometry tests in the boundary layer are planned to clarify this point.

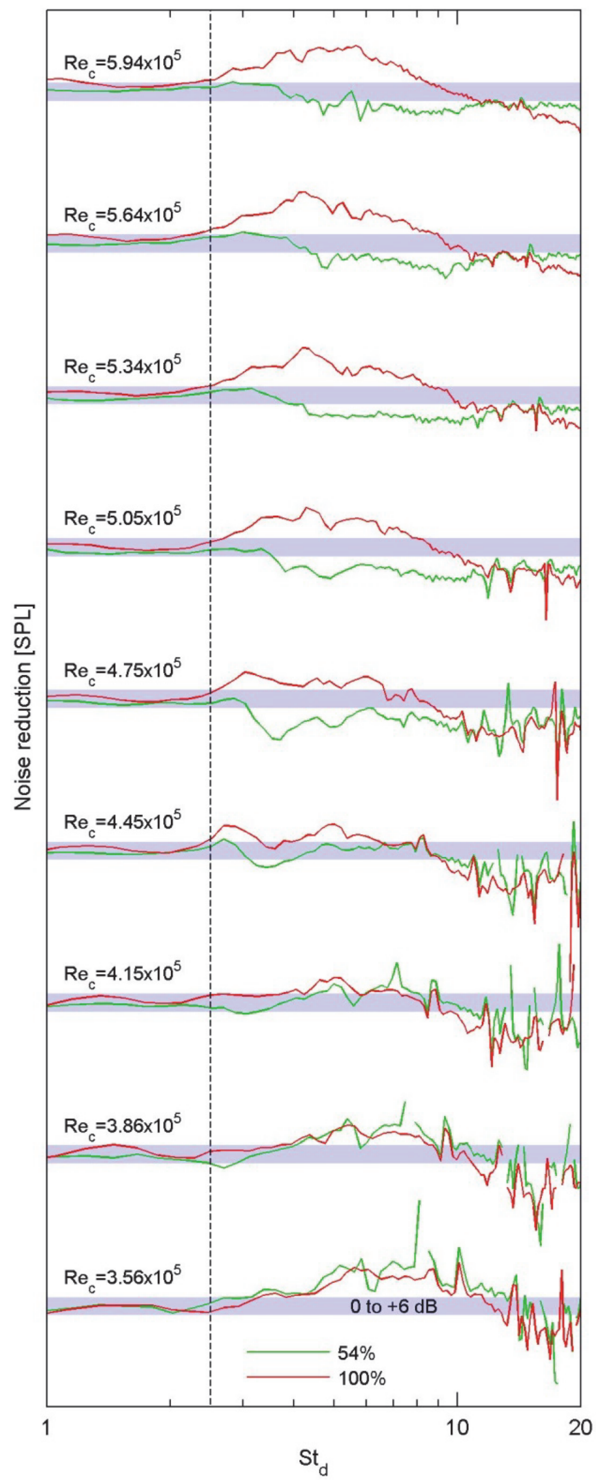

Figure 6. Noise Reduction Produced by each Porous Arrangement at all Tested Re_c

Note: In figure 6, the vertical line at $St_d = 2.5$ indicates the frequency above which the fully- and partially-porous foils do not display similar performance. The shaded region indicates 0 to +6 dB of noise reduction for each set of curves.

Regardless of the turbulent content of the flow, this report indicates that the effect of a porous foil on the acoustics is not confined to the trailing edge. Preliminary hotwire anemometry data have been acquired that show differences in the wake geometry at the trailing edge between the 100% and 0% porous foils. Additional hotwire work in the wake on an improved setup is planned for the coming year.

This report's data show that the surface of the porous foil must be permeable to flow in order to effectively reduce noise; trailing edge elasticity and acoustic impedance are secondary considerations for the material tested. This implies that the reduction in scattering is at least partially viscous, whereby the surface pressure fluctuations that would be scattered without loss in a non-porous system induce low-velocity flows within and through the porous medium, reducing the amplitude of the pressure fluctuations.

4. METHODS

4.1 DATA ACQUISITION

A line array of four Bruel and Kjaer microphones (pictured in figure 1A) was used to acquire the acoustic data at 60 kHz over 30 seconds. Spacing between the microphones was 2 inches (5.1 cm). This line array was affixed parallel to the trailing edge at the same streamwise location. The array was placed as close as possible to the trailing edge in the transverse direction without obstructing the developing shear layer produced by the jet. This distance is just over 24 inches (61 cm).

A background noise file was acquired at the beginning and end of each data session with the wind tunnel turned off. The average of these background spectra were subtracted from each data file. The spectra were produced using MATLAB's pwelch (Power Spectral Density, Welch's method) routine. The averaging window was a 512-point Hanning window with 50% overlap.

4.2 FOIL CONFIGURATION

The porous foil slices were produced using a laser cutter. This cutting procedure produces a burned layer on the surface of the foil, which is removed by sanding. This burned layer is shown partially removed in figure 1C; the darker section on the far right side of the porous section is unremoved in that image. The thickness of the felt trailing edge could not be built to the specified fineness of the NACA0012 shape following the laser cutting and sanding procedures. A thickness of ≈1 mm with some spanwise variation was measured. This trailing-edge thickness is comparable to that used by Geyer *et al*. [5].

A Kevlar thread was passed through the felt cross-sections in case it was required to stiffen the trailing edge at high angles of attack. This thread was placed 1-inch upstream of the trailing edge; figure 1D shows this thread being put in place during construction of the porous section. The stiffening was found to be unnecessary during initial trials and was removed prior to data collection.

The seam of the Spandex cover (white in figure 1A) was placed at the foil's leading edge. This introduces a mild corrugation at the leading edge. It was found that running with the cover in place removed the aeroacoustic resonance that was apparent at some speeds. This is taken as an indication that the boundary layer was sufficiently tripped at the trailing edge of the foil. Originally, a Kevlar thread was stretched over the entire span of the foil just ahead of the ¼-chord position as a trip. This was found to yield similar results, but some combinations of flow speed and tension would produce a resonant buzz that polluted the data.

The lowest Reynolds number used in the study (3.56×10^5) was selected because it was the lowest speed at which an acceptable amount of signal was obtained; figure 2A indicates that the signal-to-noise ratio is still higher than ideal at this speed. The highest Reynolds number (5.94×10^5) was the condition at which the Spandex cover began to flap.

The fairing was made of thin polyethylene. After some experimentation, standard home garbage bags were found to be sufficient for this purpose. In the 0%-porous configuration, the fairing was stretched taut around the foil. The free edge was secured with packing tape on the side of the foil opposite from the microphone array. A heat gun was then used to shrink the fairing around the foil to tighten it, with care taken not to create wrinkles in the surface.

In the 54%-porous configuration, the free edges of the fairing could not be firmly attached to the felt surface of the foil, so an alternate method was used. A seam was created in the free edge of the fairing and a Kevlar thread was run through this seam. This thread was placed under tension and secured. The heat gun was then used to shrink the fairing as in the 0%-porous case. This tensioning creates the curved rear edge of the fairing (visible in figure 1D). Stitches were then placed through the Spandex cover, fairing, and airfoil with a tapestry needle to tack the Kevlar thread to the surface. Three evenly-spaced stitches in the spanwise direction were found to be sufficient to keep the fairing from flapping.

The fairing had a tendency to "puff" slightly because of the aerodynamic loading, separating it from the felt surface. A stronger material or thicker fairing would reduce this tendency and may allow the test to be run at higher speeds. For the present test, a thin fairing was selected to better preserve the elastic qualities of the trailing edge.

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